NEW TECHNIQUES FOR ESTIMATING SOURCE DEPTH AND OTHER DIAGNOSTIC SOURCE CHARACTERISTICS OF SHALLOW EVENTS FROM REGIONAL OBSERVATIONS OF P, Lg, AND Rg SIGNALS

Shelton S. Alexander, Roy C. Hsu, and Sheri L. Karl (Penn State University)
Indra N. Gupta and David H. Salzberg (Multimax, Inc.)

AFOSR Grant No. F49620-94-1-0179

ABSTRACT

As part of a broader study to develop effective regional discriminants for Iran (and other areas of interest) a new cepstral stacking method for estimating source depth from a single, short-period regional station has been developed and tested, and new insights have been gained on why high frequency Lg/P is a very good discriminant for different source regions while low-frequency (less than about 5 Hz) Lg/P is not.

It is shown that stacking (product or sum) of the cepstra of multiple sub-windows spanning the total P and P-coda time window enhances the depth phase delays, (pP - P) and (sP - P), with respect to other delay times from crustal phases, such that accurate depth determination can be made from a single, short-period regional signal. Further enhancement can be achieved by also stacking individual stacked cepstra over multiple regional stations. The stacked product of individual cepstra gives a better result than the stacked sum, because contributions from other delay times that are prominent in some sub-windows are more-effectively suppressed in the product. The method has been tested on regional events in Iran for which multiple teleseismic pP observations are available; on Soviet Test Site (STS) nuclear explosions and one STS earthquake recorded in Iran; and on synthetic regional signals. It appears that with reasonable signal bandwidth and signal-to-noise levels accuracies in depth of about 1 km or better can be achieved for crustal events using this method.

Observations and theoretical modelling suggest that the relatively high Lg/P ratios at frequencies around 1 Hz typical of many underground nuclear explosions are caused by scattering of Rg into S-waves near the source, which in turn contributes significantly to Lg amplitudes. Rg, the short-period fundamental-mode Rayleigh wave, is well-excited in the frequency band .5 to 2 Hz by very shallow crustal sources, whereas higher frequencies are poorly excited and are also subject to signifcant intrinsic attenuation as they propagate. Besides the contributions to Lg from explosion-generated Rg, there appears to be a significant CLVD excitation of Rg at a depth about one third the shot depth. This is inferred from the presence of spectral nulls in both Rg and Lg at the same frequency and theoretical modelling to show that a null is expected for a CLVD source at that depth. Regional data from three NTS explosions and one STS explosion all exhibit spectral nulls in Lg indicating a CLVD contribution at the two test sites, which have very different near-surface and deeper crustal structure. The fact that the CLVD contribution consistently appears to come from about one third the shot depth implies that spall or related tectonic-like effects would not lead to a misinterpretation of the Rg as being generated from a source deeper than the true shot depth.

OBJECTIVES

The overall objective of this study is to develop regional discriminants such as Lg/P, Ms (or moment) vs mb, and Rg or other depth indicators for Iran. Related objectives include the transportability of discriminants developed for different tectonic source regions, determination of regional variations in various discriminants within Iran, and event identification in near-real time. Obtaining reliable depth estimates from regional signals and understanding why in general Lg/P in the frequency band .5-5 Hz is a poor discriminant while Lg/P above about 5 Hz is one of the most-effective ones are the objectives addressed in more detail in this presentation.

RESEARCH ACCOMPLISHED

In addition to the findings described below, other results of this study can be found in Alexander, et. al. (1994), Gupta, et. al. (1995). Alexander, et. al. (1995), Hsu (1995) (PhD thesis), and Karl (1995) (B.S. thesis). Data from regional events recorded at MAIO and the ILPA array in Iran have been used in the study of various regional discriminants and compared with experience elsewhere.

A very promising new cepstral stacking method (CSM) for accurately estimating source depth from a single regional signal has been developed and tested in this study and applied to Iranian as well as other regional events. The method consists of stacking cepstra of sub-windows in the P and P-coda total signal window. The sub-windows all contain the same (pP - P) and (sP - P) delay times no matter how complicated the signal is, whereas delay times for different crustal phases appear in at most a few of the sub-windows; by stacking over the sub-windows the common, depth-phase delay times are enhanced while those for the distinct crustal phases are not. It was found that stacking using the product of individual sub-window cepstra is more effective than using the corresponding sum; this result most likely reflects the fact that a strong cepstral peak from crustal phase delay times present in a few of the sub-windows affects the product much less than the sum. Although arbitrary and not yet fully explored, it appears that overlapping the sub-windows by about 75 percent produces the best results. Further enhancement can be achieved by stacking these individual stacked cepstra over several regional stations, if more than one regional station records an event.

To assess the effectiveness of this new cepstral stacking method it was tested on different Iranian events that have several consistent and independent teleseismic pP arrival times listed in the ISC bulletin; on several known Soviet test site (STS) underground nuclear explosions and a nearby earthquake recorded regionally at MAIO in Iran; and on synthetic regional signals for earthquake and explosion sources at different depths. Figure 1 shows an example of an Iranian event recorded regionally at ILPA which had several independent pP arrivals in the ISC bulletin all giving a (pP - P) delay time of 7.1 seconds corresponding to a depth of approximately 21 km. The very prominent cepstral peak in Figure 1 gives almost exactly the same delay time. Figure 2 shows the result of stacking individual stacked cepstra over three stations in the ILPA array; one sees that the depth-phase peak at 7.1 seconds is further enhanced. Another important example is shown in Figure 3 for a known STS underground nuclear explosion at Degelen and a nearby earthquake of

nearly the same mb recorded at MAIO; the cepstral peak for the explosion occurs at a delay time of less than 1 second while that of the earthquake occurs at a delay time of approximately 3 seconds corresponding to a source depth of about 9 km. Because these events traveled virtually identical paths and were recorded by the same receiver, any differences must reflect only source differences, depth in this case. It should be noted that these events could also be discriminated on the basis of Lg/P differences observed at MAIO.

Based on the assessments of the CSM done so far, it appears to provide a powerful new tool for obtaining reliable source depths using only a single regional station or a very sparse regional network. While the emphasis here is on verification in particular areas of interest, in this case Iran, the method is applicable in general for estimating source depths of earthquakes or explosions anywhere.

Observations and a theoretical model suggesting that the low-frequency (.5 to 2 Hz) Lg from nuclear explosions is mainly due to the near-source scattering of explosion-generated Rg into S have been recently provided by Gupta *et al.* (1992). This mechanism has been supported by the analysis of regional data from several Yucca Flats, Nevada Test Site (NTS) explosions by Patton and Taylor (1995) who further argued that the prominent low-frequency spectral null in Lg is due to Rg from a CLVD source and is related to its depth. In this study, we examined the time-varying spectral characteristics of the observed seismic arrivals by narrow bandpass filtering (NBF) which provides amplitudes versus group velocity and period. NBF of synthetic seismograms generated using wavenumber integration shows the presence of a prominent spectral null for the CLVD source. For the Rainier Mesa (NTS) explosion, Mineral Quarry, data at several local and regional distances are available; NBF analyses show that the spectral null in the Rg-S wave-group at local distances is also observed in Lg at regional distances, indicating that the Rg spectrum is imprinted onto the scattered S waves (e.g. Figure 4). Similar analysis of regional data from two Yucca Flats (NTS) explosions at shot depths of 503 and 396 m, indicates prominent spectral nulls in Lg at periods of about 1.5 and 1.1 sec, respectively. Observations of a pronounced spectral null (at period about 0.7 sec) in regional data from a Soviet nuclear explosion (Figure 5) imply that the mechanism of generation of the low-frequency Lg at NTS and East Kazakh test sites, with completely different crustal structure and tectonics, is similar. Spectral nulls provide an estimate of depth of the CLVD source, which in our study appears to be nearly one-third of the depth of burial. These results together with other source information are summarized in Table 1.

TABLE 1
Observed Spectral Nulls and Source Information

Shot Name	Null T (sec)	DOB H (m)	Velocity (overburden) α (m/sec)	CLVD Depth $h = (\alpha T)/16$	h/H
Mineral Quarry	1.8	389	2200*	250 m	0.6
Texarkana	1.5	503	1720	160 m	0.3
Tulia	1.1	396	1530	110 m	0.3
Kazakh JVE	0.7	600 est	4600#	200 m	0.3

In summary, NBF analyses of data from Mineral Quarry show that, at the higher frequencies, Rg gradually scatters into body phases that travel with faster group velocities. The spectral null in Rg at local distances also appears in Lg at regional distances, indicating that the Rg spectrum is imprinted onto the scattered S waves. Regional data from three NTS shots and one East Kazakh test site indicate distinct spectral nulls in Lg, apparently due to the CLVD source associated with each explosion. This means that an effective CLVD source is present not only for explosions at the Yucca Flats (as demonstrated by Patton and Taylor, 1995) but also at other sites with considerably different near-surface and deeper crustal structure. Spectral nulls may provide estimates of the CLVD source depth which appears to be nearly one-third of the depth of burial for three out of four shots used in this study. Narrow band-pass filtering, combined with theory, may provide useful source and near-source information about underground nuclear explosions and improve our understanding of the generation of low-frequency Lg from underground explosions. There is clearly a need to further test and exploit these preliminary results by examining much more local and regional data from several latest sites.

REFERENCES

Alexander, S. S., C. Hsu, I. N. Gupta, and D. H. Salzburg, (1994). Development of discriminants and improved locations for regional events in Iran, Proc. 16th Annual Seis. Res. Symposium, 13-19. PL-TR-94-2217, ADA284667

Gupta, I. N., W. W. Chan, and R. A. Wagner (1992). A comparison of regional phases from underground nuclear explosions at East Kazakh and Nevada test sites, Bull. Seism. Soc. Am. 82, 352-382.

Gupta, I. N., D. H. Salzberg, and S. S. Alexander (1994). A study of regional discriminants for seismic events in Iran, EOS 75, no. 44, 428 (abstract).

Gupta, I. N. and D. H. Salzberg (1995). Observations of spectral null in Lg from underground explosions at the Nevada and Kazakh test sites, EOS 76, no. 17, S205 (abstract).

Hsu, C. (1995). Seismic Signal Pattern Recognition, Ph.D. Thesis, EE, The Pennsylvania State University, 185 pp.

Karl, S. L. (1995). Magnitude and source depth estimates for earthquake and explosions in Iran--regional observations, B.S. Thesis, Geosciences, The Pennsylvania State University, 79 pp.

Patton, H. J. and S. R. Taylor (1995). Analysis of Lg spectral ratios from NTS explosions: Implications for the source mechanisms of spall and the generation of Lg waves, Bull. Seism. Soc. Am. 85, 220-236.

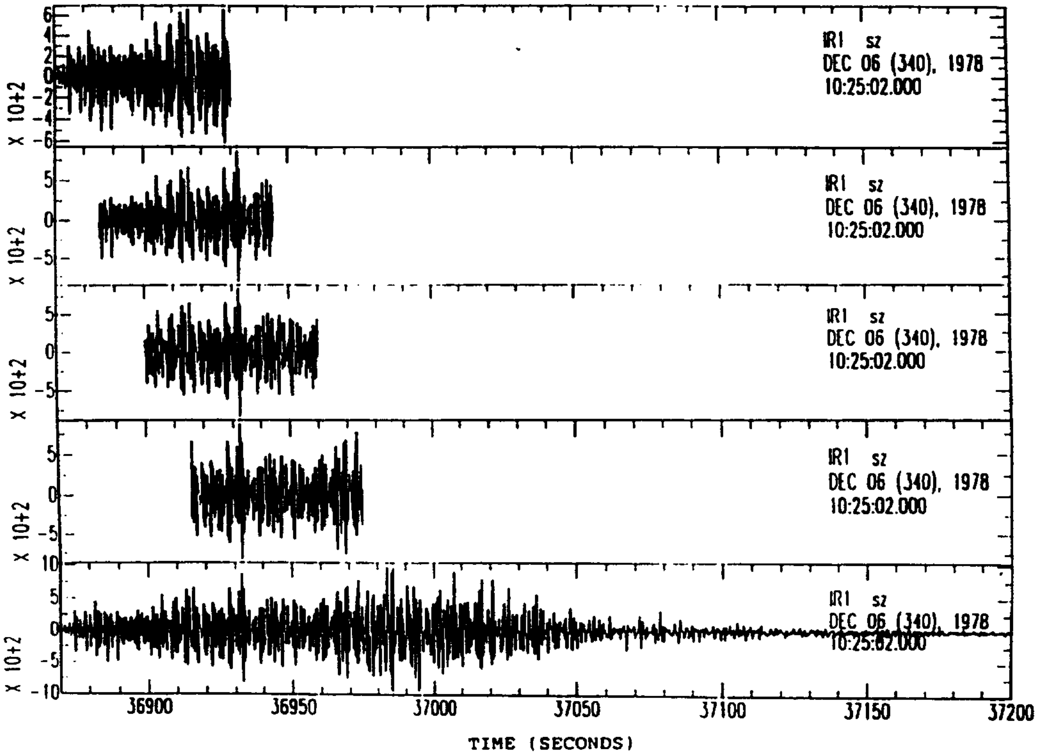

Figure 1a. Regional earthquake signal recorded at ILPA station IR1 and four sub-windows used for cepstral stacking. The epicentral distance is 638 km.

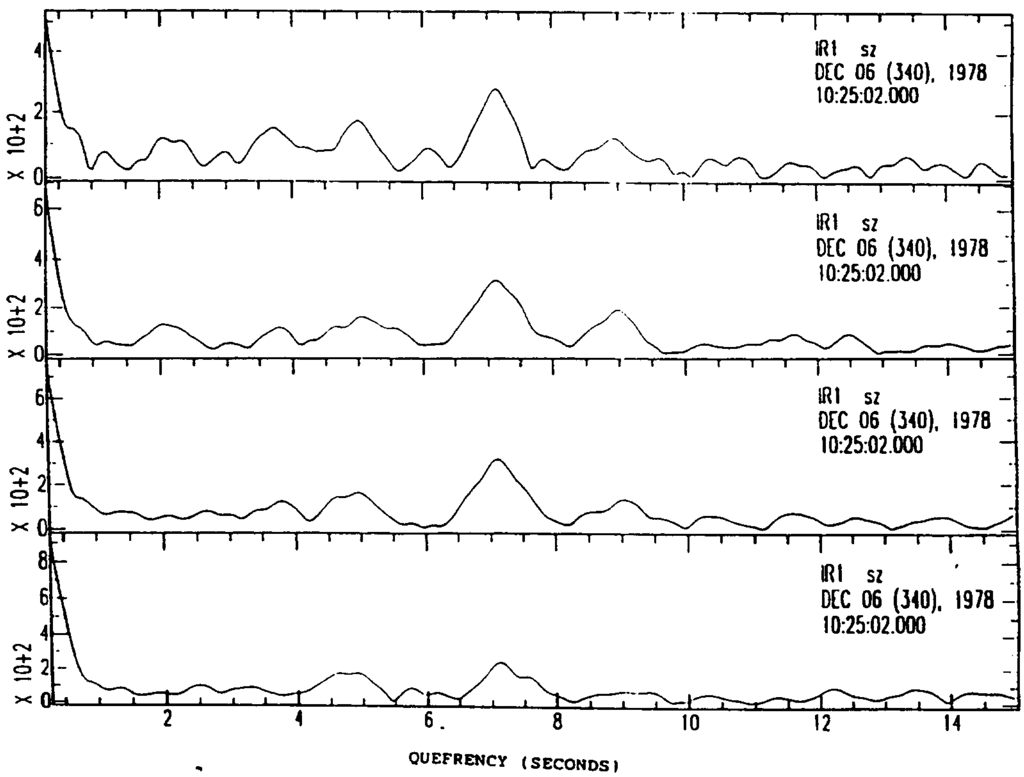

Figure 1b. Individual cepstra of sub-windows in Figure 1a.

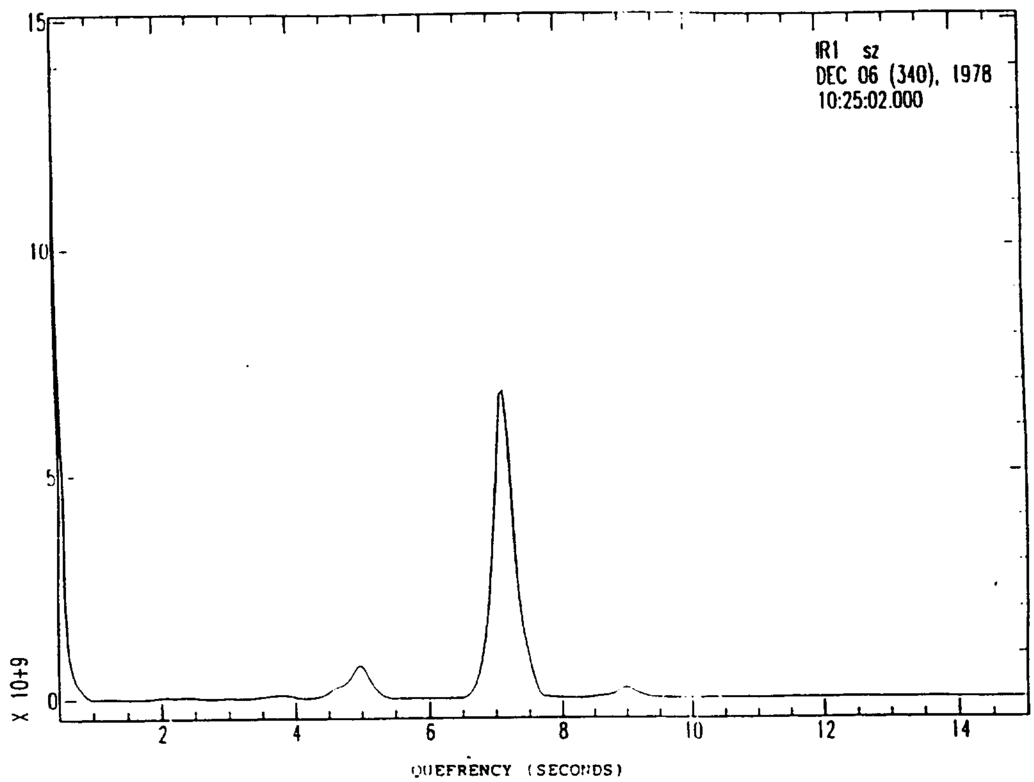

Figure 1b. Stacked cepstra of sub-windows in Figure 1a.

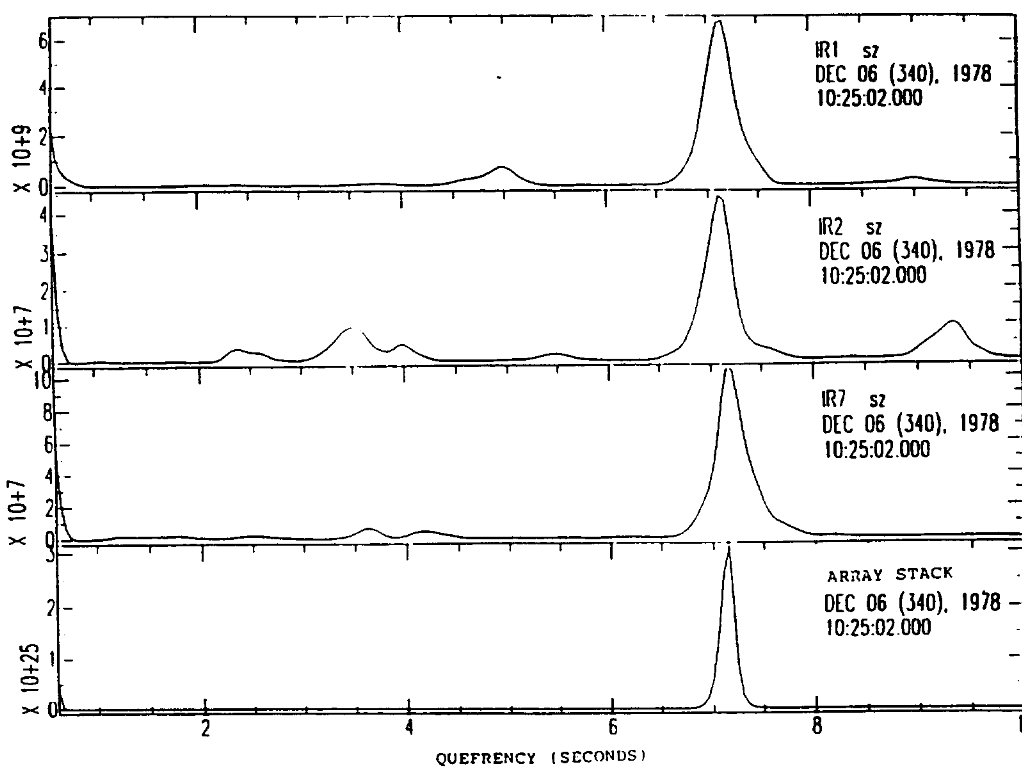

Figure 2. Individual cepstra stacked over three stations in the ILPA array for the event shown in Figure 1a.

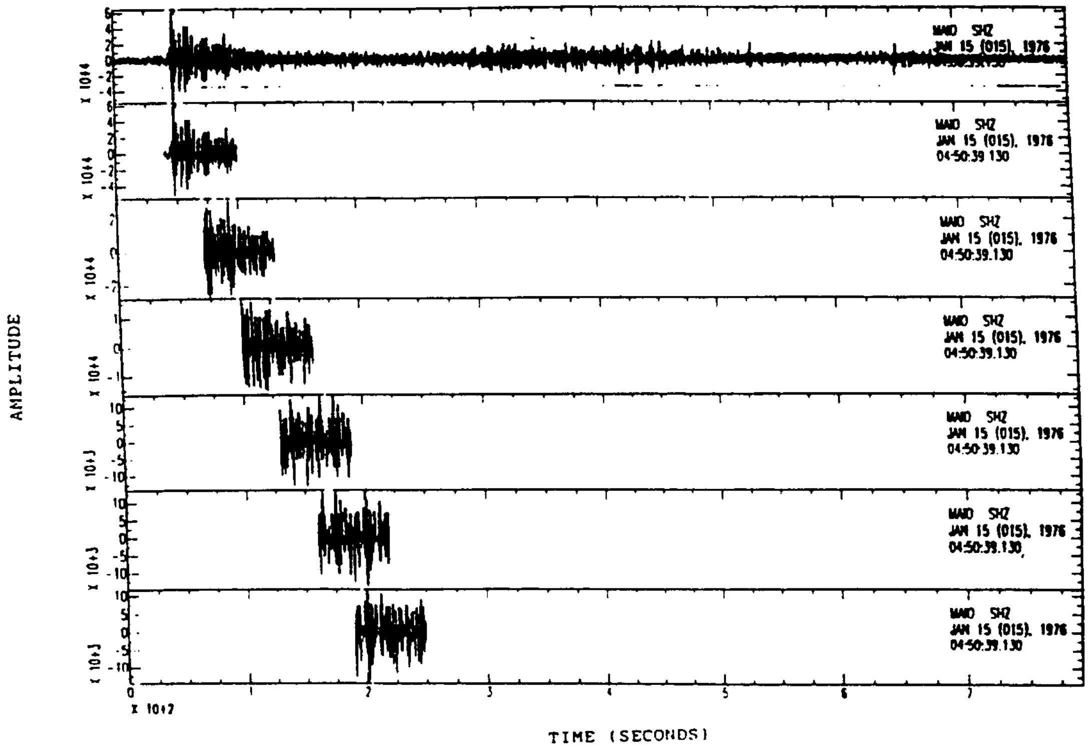

Figure 3a. Signal observed at MAIO for a mb 5.2 underground explosion at Degelen and the sub-windows used for cepstral stacking. Distance = 19.2 deg.

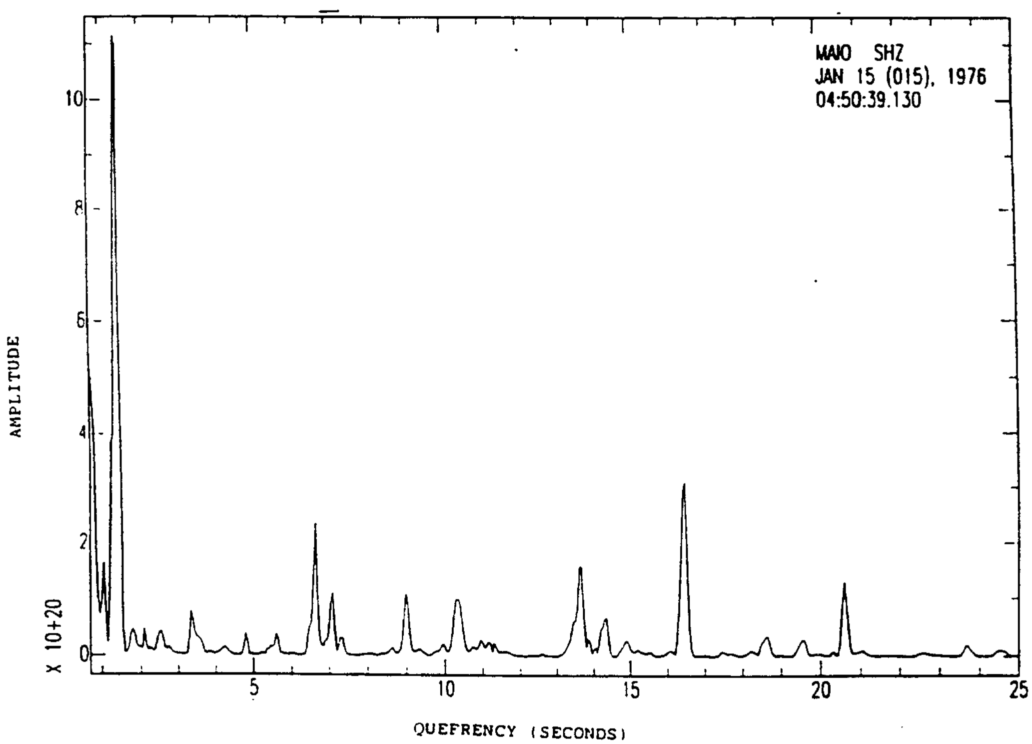

Figure 3b. Stacked cepstra for the STS explosion shown in Figure 3a.

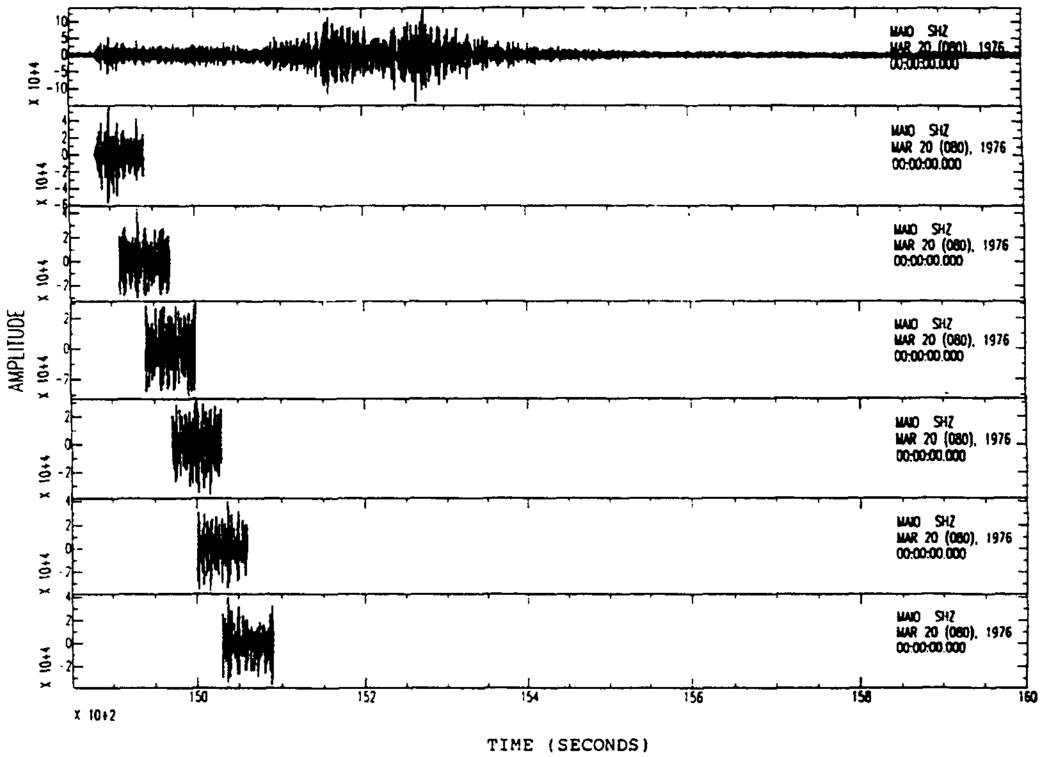

Figure 3c. Signal observed at MAIO for a mb 5.1 earthquake near Degelen and the sub-windows used for cepstral stacking. Distance = 18.8 deg.

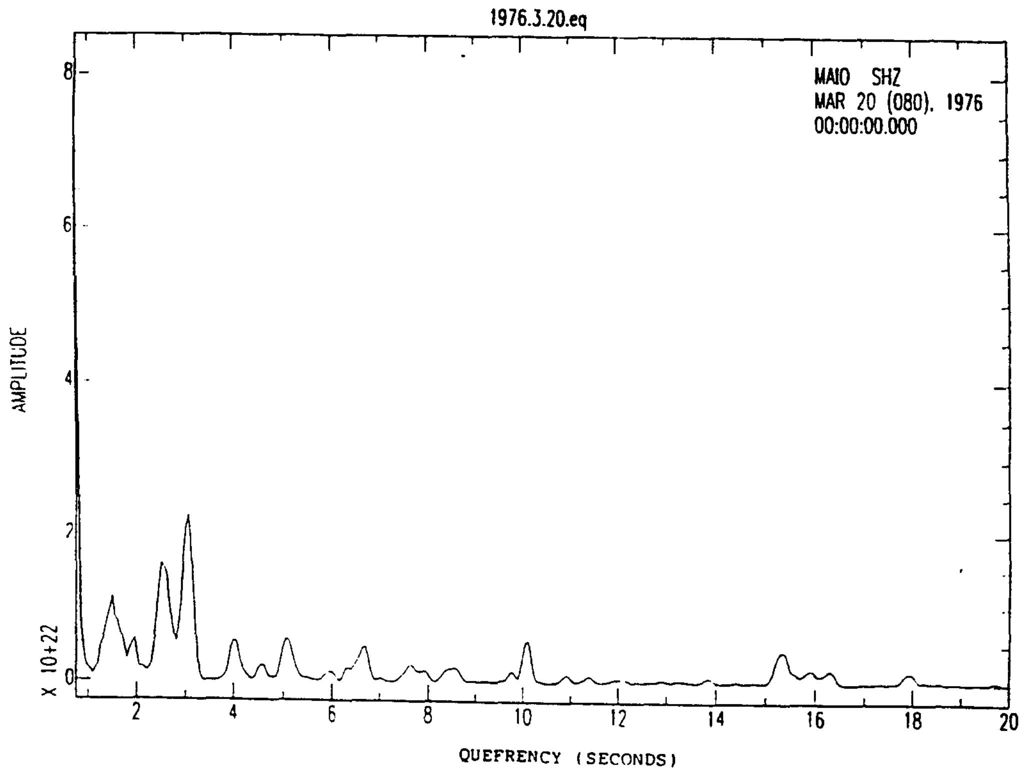

Figure 3d. Stacked cepstra for the STS earthquake shown in Figure 3c.

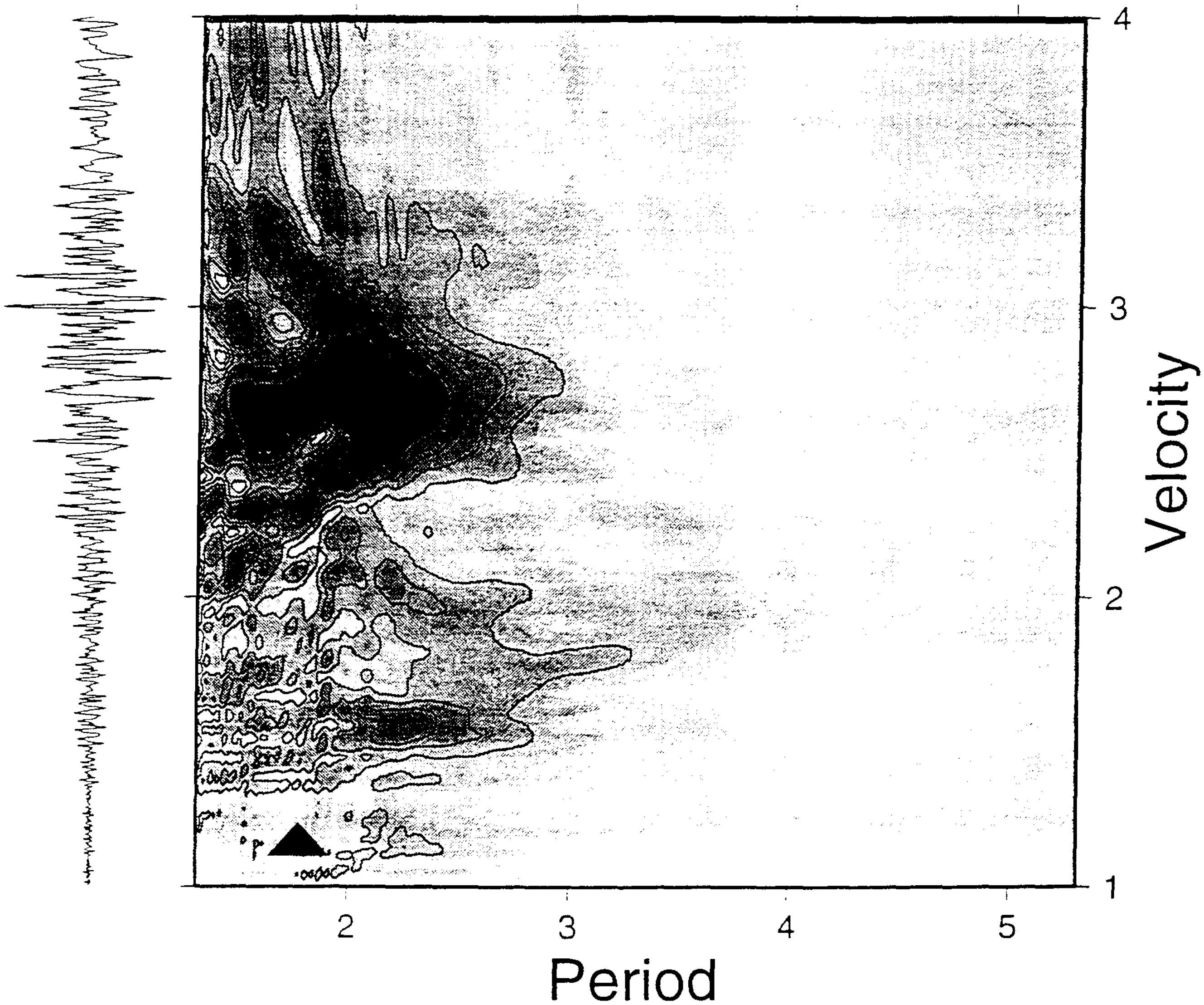

Figure 4. NBF of vertical component data recorded at the regional station DRW, about 160 km southwest of the shot point. Note the spectral null at period of about 1.8 sec in both Lg (velocity about 2.7 km/sec) and Rg (velocity about 1.5 km/sec).

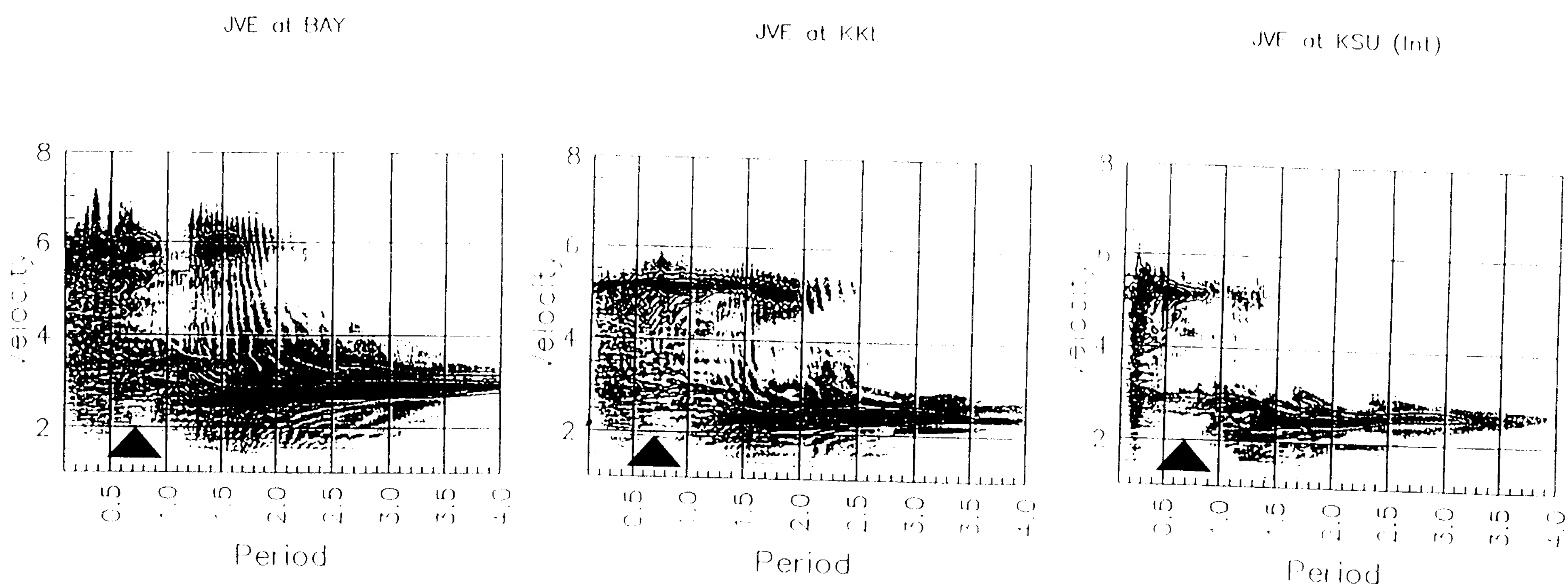

Figure 5. NBF of vertical component data from the Kazakh test site explosion of 14 September 1988 recorded at (a) KSU, 160 km east, (b) KKL, 255 km southwest, and (c) BAY, 255 km northwest, each showing spectral null in the S-wave group or Lg at a period of about 0.7 sec.